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An Introduction to the Functionality of the ISAR Radar

RICHARD MADDEN

Radar Analysis Branch
Radar Division

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There are many types of sensors to sense or analyze most any type of environment, environmental conditions, or even targets that are of interest. Radar, which is only the broad definition, is a remote sensor.

Many different types of radar are in use. ISAR radar is in use by the U.S. Navy and the Coast Guard. The ISAR radar was first realized in the early 1970s and, even after almost thirty years of existence, there isn't one book that has explained the fundamentals of ISAR radar.

There have been many articles in the trade journals about ISAR and how to improve the radar. Someone new to the field would have to go through the many articles on ISAR and the many articles and books on SAR.

Even though ISAR is very signal processing oriented, this report is not. The purpose of this report is to introduce some of the basic principles of the ISAR radar and how it works. Some explanation of the type of information a trained individual can exploit from an ISAR image is also included.

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I. Introduction

The history of Radar is a fascinating one and there have been many discoveries in radar. To this date, there are many new discoveries being made with radar. There are many different types of radar, such as weather, surveillance, fire control, SAR (Synthetic Aperture Radar) and ISAR (Inverse Synthetic Aperture Radar) . This short list names a few. What type of radar being used also determines what an individual is actually trying to observe or sense with the radar. This paper will provide a simplistic approach in describing basic understanding of ISAR radar operations.

When people started trying to use SAR radar to image ships at sea, the image was blurred due to the motion of the ship. The ISAR radar is imaging radar that uses the motion of a target to develop the image. The term target used in this context describes any object in which the radar is imaging. ISAR radar true beginnings were in the early 1970's.

II. The Advantage of ISAR

It was observed that SAR images would tend to blur or defocus if there was motion of the target within the frame of reference. ISAR processing exploits the target's motion to produce a "clear" image of what was causing the blurred effects of the SAR image. The basic motion that contributes to the ISAR image of a target is roll, pitch, and yaw. Roll and pitch are responsible for the generation of the profile views that exhibit height information, while the yaw generates a plan view as seen in Figure 1. There are other factors that contribute to the process of generating an ISAR image. One such factor is the aspect angle between the radar and the target. There are three possible scenarios for the aspect angle while viewing a target image. The radar may be pointing directly at the bow or stern, otherwise known as "end-on" aspect. It may be pointing directly broadside (perpendicular) to the target, or at any angle in between. The other factor is obviously the height of the sensor. These factors and how they affect the image will be explained in more detail later.

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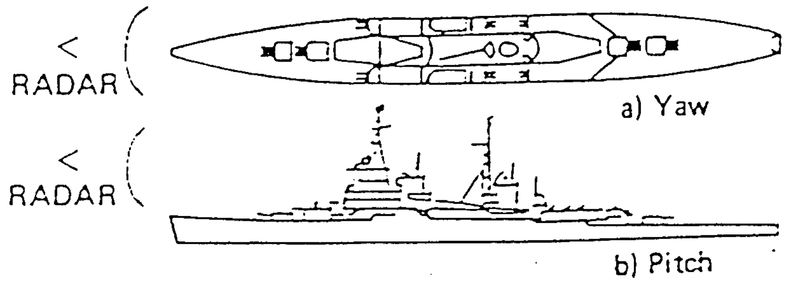

Figure 1 Yaw and Pitch Creates Plan and Profile

II.1 Ship Classification

The military quickly noted the advantage of using such radar and began to study ways in which this radar could be fully utilized. It was easily foreseeable that this radar could be used in classification of targets and battle damage assessments of targets. ISAR provides basically a contour of the target that it is imaging. From this contour image and some training, an individual would be able to at least classify the image based on the returns of the target. The military found this particularly useful in ship classification. Usually a ship or an aircraft would have to get close enough to see the ship in which it was trying to classify. This could potentially be a very dangerous situation in hostile enviroments. At such close range, the observing ship or aircraft would be within missile range of the ship being classified. With ISAR radar on an airborne platform, classification of another vessel could be done outside the range of a missile attack.

II.2 Battle Damage Assessment

Battle damage assessment was also recognized as a potential use of ISAR radar. The operator of the ISAR radar would quickly be able to determine if there was major damage such as a hole in the ship's hull or if a ship's mast missing from the ship. Battle damage assessment is important because it can be determined if a first attack has caused enough damage so that the target is no longer a treat. ISAR thus has the potential to be a force multiplier.

III Basic SAR Principles

ISAR is easily explained by reviewing some basic principles of SAR in spotlight mode. Therefore the processing that is used to form spotlight mode SAR Imagery will be outlined.

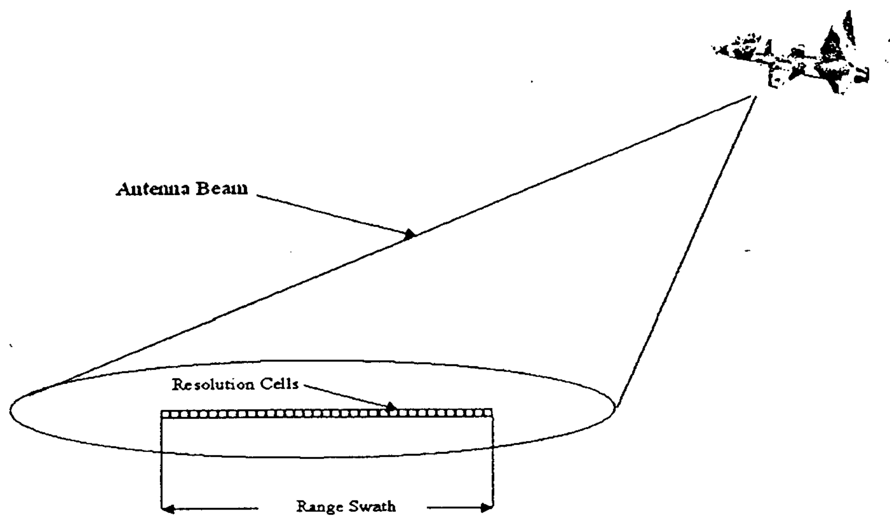

Figure 2 Example of Range Bin Resolution Cells.

The radar sends out a pulse, which reflects off the target, and the receiver listens for this pulse to return. As these pulses are returned and collected, there is a sum of returns that built up within each range bin. Figure 2 shows a visual representation of range bins within an antenna beamwidth. This sum comes quite close to representing the total return from scatterers within a single range/azimuth resolution cell. The contents of the bank of range bins represent the returns from a single row of resolution cells spanning a swath.

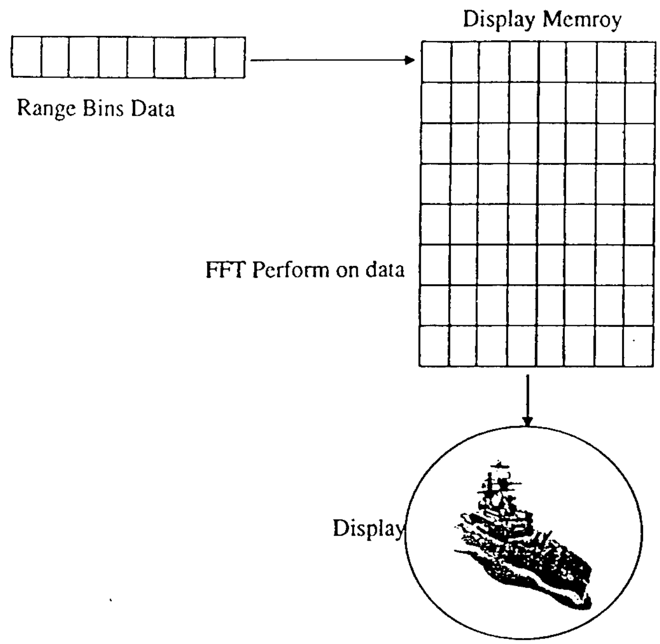

Figure 3 Range bins are transferred to video memory.

Figure 3 shows that at this point, then contents of the individual range bins are transferred to corresponding locations in a matrix stored in memory. The signal processor then begins forming the image from this matrix, which consists of the data collected. The range data from a pulse is stored in a row in the matrix and when the rows of the matrix is filled, an FFT is preformed on each column to produce the image.

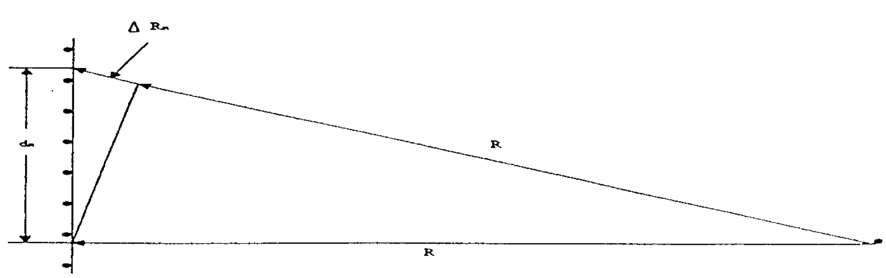

Figure 4 Phase error results when target is off boresight of the main beam

III.1 Phase Error Corrections

If the target is not locataed on boresight of the antenna, a phase error is introduced into the returns from the target, which must be compensated. The case for a linear array of targets is shown in Figure 4. The process of correcting this phase error is called focusing the array. This phase compensation is a rather simple calculation based upon geometry.

$$(R+\Delta R_n)^2 = R^2 + d_n^{\ 2}$$

$$R^2 + 2R\Delta R_n + \Delta R_n^{\ 2} = R^2 + d_n^{\ 2}$$

$$2R\Delta R_n(1+\frac{\Delta R_n}{2R}) = d_n^{\ 2}$$

Now assuming $\Delta R_n << 2R$ then,

$$\Delta R_n \cong \frac{d_n^{\ 2}}{2R}$$

Therefore the phase error becomes

$$\phi_n = \frac{2\pi}{\lambda}(2\Delta R_n) = \frac{2\pi}{\lambda}\frac{d_n^{\ 2}}{R}$$

where

d_n = distance of element n from array center

λ = wavelength

R = range to area being mapped.

The process of focusing the array and integration to form the image occurs between the memory of the range bin data and display memory. As the returns from any one transmitted pulse come in, they are stored in the top row of the matrix. When the return from the most distant range cell has been received, the contents of every row are shifted down to the next row below to make room for the incoming returns from the next transmitted pulse. This is called line by line processing.

III.2 Rotating the Signal

The signal processing for focusing an array must perform an equivalent of rotating each successive array element (n) through the phase angle ϕ_n. To perform the rotation, as seen in Figure 5, the following transformations must be computed.

$$X_n^{'} = X_n Cos\phi_n + Y_n Sin\phi_n$$

$$Y_n^{'} = Y_n Cos\varphi_n - X_N Sin\varphi_n$$

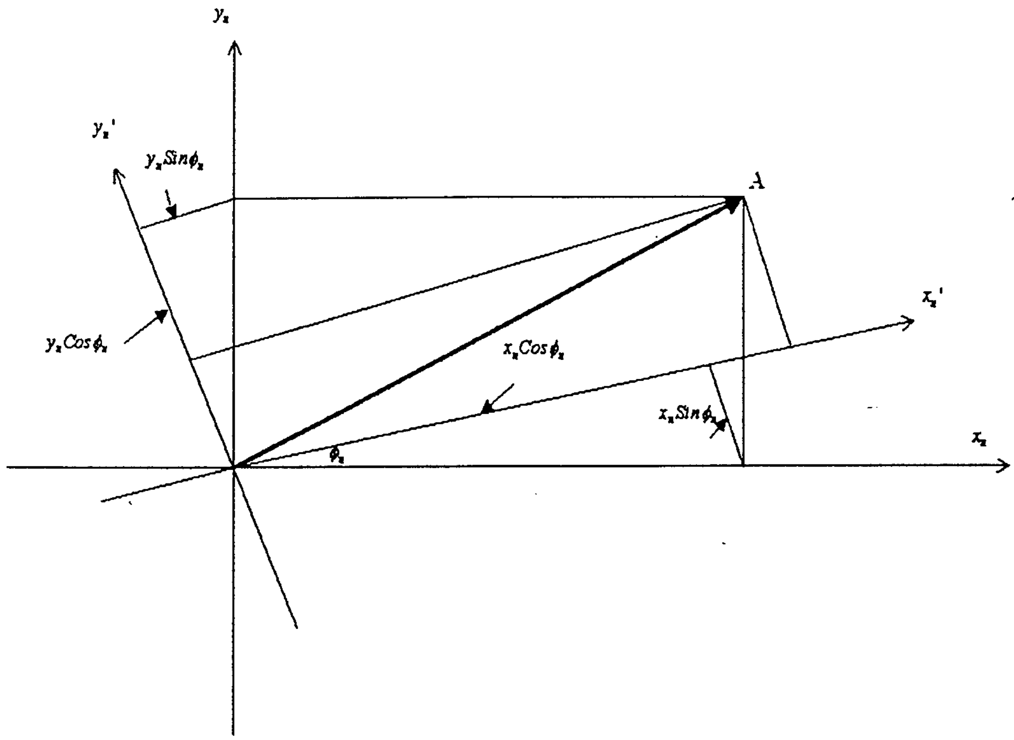

Figure 5 Rotating the signal.

Where X_n and Y_n are the I and Q components of the phasor, representing a single received sample, before rotation. And X_n' and Y_n' are the components after rotation. Next, the rotated components must be summed for the total number of array element (N)

$$X = \sum_{n=1}^{N} X_n'$$

$$Y = \sum_{n=1}^{N} Y_n'$$

Next the magnitude of the vector sum of X and Y must be calculated

$$S = \sqrt{X^2 + Y^2}$$

The process of rotating the signal is the same as the Discrete Fourier Transformt (DFT) algorithm and represents another way of viewing the image formation process. The reason the DFT is used for image formation is because the DFT is the Fourier representation of a finite length sequence that is a discrete sequence rather than a continuos function. Thus the DFT, implemented usually by the Fast Fourier Transform (FFT), is the primary algortihm used in conventional ISAR image processing.

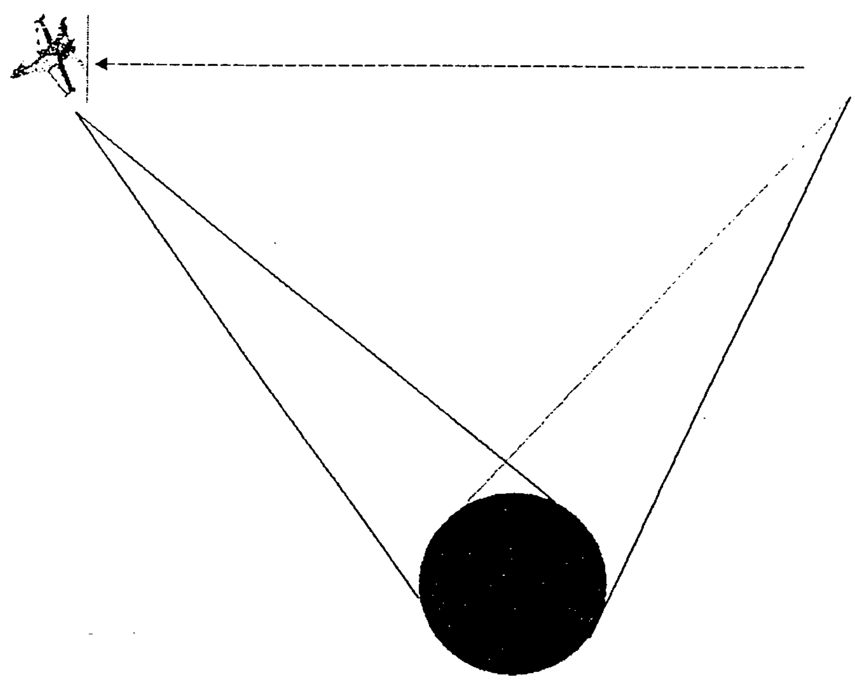

Figure 6 Geometry for SAR spotlight mode is when the antenna beam width is concentrated over a particular area of interest

III.3 Spotlight Mode SAR

ISAR can be thought of as a form of SAR spotlight mode for a moving target. In spotlight SAR, as the radar moves along the flight path as shown in figure 6, the main beam width of the antenna illuminates a particular area of interest. This is done by gradually changing the look angle of the antenna as the radar travels a particular distance. As the radar travels and the look angle changes, the appropriate phase corrections previously described must also be performed. This improves the quality by moderating the scintillation. Scintillation is fluctuations in the amplitude of the return received from a target. It is caused due to relative changes in the reflected signal of the various scattering elements that make up the target.

IV. Simple ISAR Principles

Sensing the target's translational and rotational motion relative to the radar platform and coherently processing the radar signals develops the ISAR radar target images. The change in aspect due to the motion between the radar and target provides the cross-range dimension needed to form an image. Individual scatters on the target are resolved in range because of the fine time sampling capabilities of the radar. Range refers to the slant range of the target to the radar. The targets are resolved in cross range by coherent integration of the return signal.

IV.1 Frequency Stepping

One method in achieving good quality images is frequency stepping waveforms. High speed analog to digital converters are needed to achieve a high range resolution. The transmitted radar frequency and the receiver local oscillator reference frequency are stepped from pulse to pulse. Once a group of radar echoes is stored in the signal processor, a discrete Fourier transform is performed to obtain the synthetic range profile. The range resolution is the reciprocal of the total span of the frequency stepping bandwidth. One should note that the frequency stepping technique assumes that the pulsewidth covers the full range extent of the target.

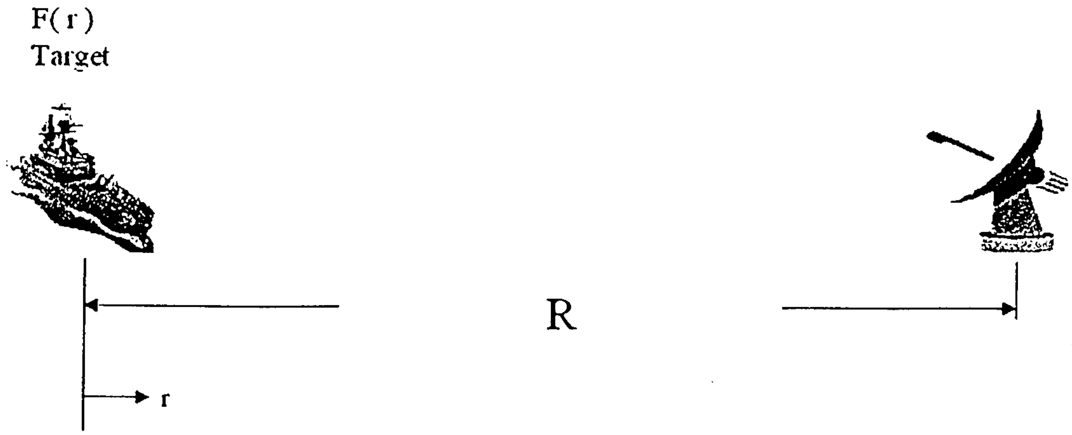

Figure 7 A Target R distance from the radar fluctuating as F(r)

Figure 7 shows a target at a distance R from the radar. F(r) is the target reflectivity function. The frequency of each successive pulse is increasing monotonically by ΔF_r within each burst. The radiated frequencies are

$$F_k = F_o + k\Delta F_r$$

where k = 0, 1, 2,...,n-1

The radar now listens for the return echo. These returns from the target can be expressed with the following equation.

$$G(k) = I_k + Q_k = A\int F(r)e^{j\frac{4\pi}{c}(F_o + k\Delta F_r)(R-r)}dr$$

As stated before, the frequency stepping technique assumes that the pulsewidth covers the full range extent of the target and this expression also assumes this condition. A is a scale factor which

accounts for any loss due to signal propagation. One should also note that G (k) is a discrete complex function of frequency. The target reflectivity function f(r) can also be reconstructed by performing a Fourier transform on G (k). This is true because the frequency step $\Delta f\, r$ is a constant through all frequency steps.

From this equation, other information maybe obtained, but first the equation can be rewritten as

$$G(k) = Ae^{-j\frac{4\pi}{c}(F_o+k\Delta F_r)R}\int F(r)e^{+j\frac{4\pi}{c}(F_o+k\Delta F_r)r}dr$$

It is easily deducted that this equation has two parts. The returns have a component that is constant over a group of pulses which is shown as Ae^{-jxR} and the other component, $f(r)Ae^{+jxr}$, is range dependant. Where X is defined as

$$X = \frac{4\pi}{c}(F_o + k\Delta F_r)$$

The range dependant component is used for generating the high resolution range data where the range varies over a function of time and can be thought of as R(t) and therefore G(k) becomes G(k,t). The equation now becomes

$$G(k,t) = Ae^{-j\frac{4\pi}{c}(F_o+k\Delta F_r)R}\int F(r)e^{+j\frac{4\pi}{c}(F_o+k\Delta F_r)R(t)}dr$$

The variability of R is discussed later in the motion compensation section

IV.2 Range Resolution

This equation now tells us that if two scatters were separated by Δr, then they would appear in the same range bin. Here

$$\Delta r = \frac{c}{2F(r)} \; .$$

This is the unambiguous range which can be obtained from the Fourier transform of G(k,t).

Since there are N range bins obtained from the N-point FFT over the returns from the radar, the range resolution Δr_r is

$$\Delta r_r = \frac{\Delta r}{N} = \frac{c}{2B_r} \; .$$

Where B_r is the effective bandwidth of the high-resolution pulse from N frequencies stepped at Δf_r pulse to pulse. This actually shows that the range resolution is purely a function of total effective bandwidth and thus independent of the instantaneous bandwidth from any individual pulse.

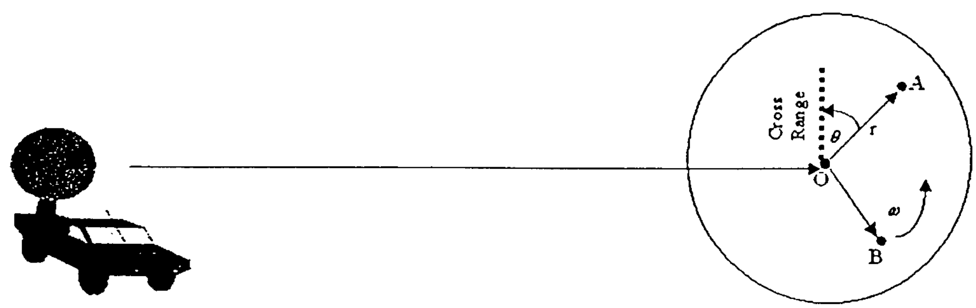

Figure 8 Geometry configuration for cross range.

III.3 Cross Range Resolution

The next step is to talk about the cross range resolution of the ISAR radar. If we take two distinct scatterers, Points A and B located on a target that rotates with an angular rate of ω, these points will have a

separable Doppler rate. Figure 8 shows one such case and in this example the Doppler returns consist of one positive and one negative. The Doppler frequency F_D of the return produced by the scattering points is given as follows:

$$F_D = \frac{r\omega\cos\theta}{\frac{\lambda}{2}}$$

r is the distance from the points (A and B) to the center of rotation,

ω is the angular rate,

θ is the angle between OA and the cross range axis, and

λ is the transmitted wavelength.

The separation between the Doppler frequencies, when the two scatterers are seperated in cross range by a distance Δr_c , is described by the following equation

$$\Delta f_d = \frac{\Delta r_c \omega}{\frac{\lambda}{2}} .$$

The cross range resolution Δr_c depends upon how well the frequency difference can be resolved. The frequency resolution Δf_d is the difference in the Doppler frequencies from the two scatterers in the same slant range cell, but separated in cross range by a distance Δr_c . The cross range of a target is expressed as an aspect angle change, ψ.

$$\Delta r_c = \frac{\lambda}{2\omega T} = \frac{\lambda}{2\Delta\psi}$$

For better images, the range and cross range resolution should be equal. This will provide some symmetry of the target.

IV.4 Motion Compensation

There are two parts to the motion of the target. One is the translational motion, while the other is rotational motion. The target's rotational motion is the part of the target motion that assists in the formation of the ISAR imagery. The phase modulations due to translational motion of the target must be eliminated by motion compensation. Successful motion compensation is a critical technique for ISAR radars. This must be done before any imaging can be done.

The motion compensation can be realized by range realignment and phase compensation. Range realignment aligns high-resolution range profiles in the range direction by placing the returns of different pulses resulting from the same scatter in the same range cell. After the range realignment process is completed, then any residual motion error is eliminated by phase compensation. The phase compensation is based on a reference range cell that contains a strong scatterer. If there is no strong scatterer, then an estimate of the pulse-to-pulse phase difference of a reference point can be made by taking the phase difference for each range cell and averaging them. The amplitude of each range cell weights each of the average phases difference from each of the range cells. There are techniques to estimate the phase of the translational motion. Once the phase estimation is performed on a target, then this phase information can be "backed out" of the returning radar signal and thus, eliminate translational motion of the target.

IV.5. Image Mapping Methods

After the translational motion of the target has been compensated, the next step is to image the target. This is accomplished by mapping the received radar signals of the target into two-dimensional (2-D) plane. A bank of matched filters that defines different locations within the 2-D image plane achieves this mapping. There are two methods that achieve this approximation. The first is the linear imaging approximation and the other is known as the wide angle imaging approximation.

Linear imaging approximation is the most common. Recalling the equation

$$G(k,t) = Ae^{-j\frac{4\pi}{c}(F_o + k\Delta F_r)R} \int F(r) e^{+j\frac{4\pi}{c}(F_o + k\Delta F_r)R(t)} dr,$$

the assumption is that R in equation of the target returns varies only as a linear function of θ. The term's the part before the integral represents complex motion of the target. The linear angle variation is kept only in the phase term, and a constant range approximation is used in indexing the range profile. The assumption is made to keep the one-way range function simple. The problem with this method is that uniformed spaced angle samples are used and that the scattering center must remain within a range and cross range resolution cell during the entire imaging interval. When the scattering center does not conformed to this constraint (stay within the resolution cell), the scattering center is said to "walk" out of the resolution cell.

Wide-angle resolution seems to solve this "walking" problem of the scattering center. This variation of imaging uses linearity, but only where the linearity estimation is valued. Basically if the scattering center "walk" out of the resolution cell during an imaging interval, it will segment the pulses of the image interval and use only the portions of the segmented pulses where linearity consists. The partitioned pulses are then used to form a linear image. This process is referred to as subapertur processing.

IV.6 Length and Width from an Image

As stated previously, ISAR is used extensively for target classification. Although the outline of the ship, (the ISAR image), can yield a great deal of information, such as how many mast, super structure placement, etc., it usually is not enough information in classifying the target. The next question is, "Is there any other information that a radar operator can acquire from the image?" Obviously the answer is yes. Some of the "simple" information that can be acquired from an image is the length and the width. I use the term "simple" loosely. Even though the length and the width of the target seems to be trivial information, this information provided to a trained radar operator could prove invaluable in target classification.

To calculate the length and the width, a basic understanding of Pythagorean relation of a right triangle is needed. This trigonometric identity that is most important is stated as:

$$c = \sqrt{a^2 + b^2}.$$

There are other factors that should be taken into account when trying to get the actual length and width of a target from an image such as the distortion of the image plane. These factors are complex and often subjective and will not be discussed within the scope of this paper.

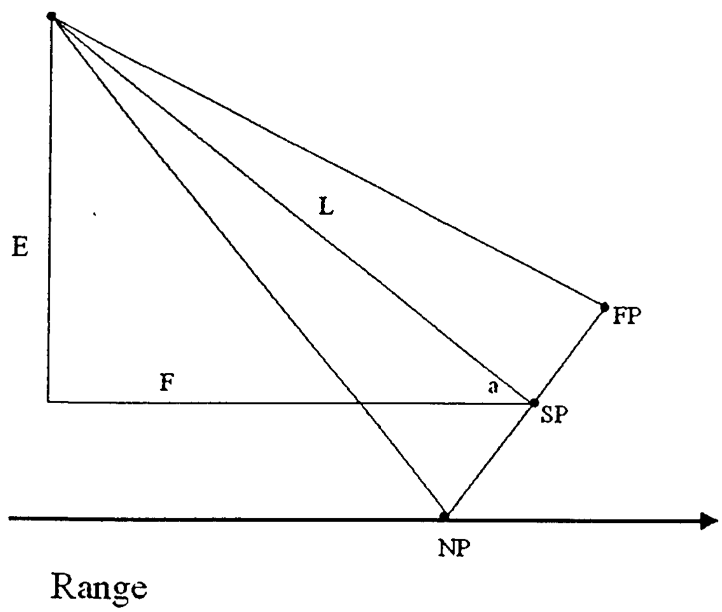

Figure 9 Geometric configuration for calculating length of a target.

As seen from the figure 9 above, the length L of the target is simply applying the trig identity. From this calculation, the length would be calculated as follows:

$$L = \sqrt{E^2 + F^2}$$

Where NP is near point, SP is scartering point, and FP is Far Point.

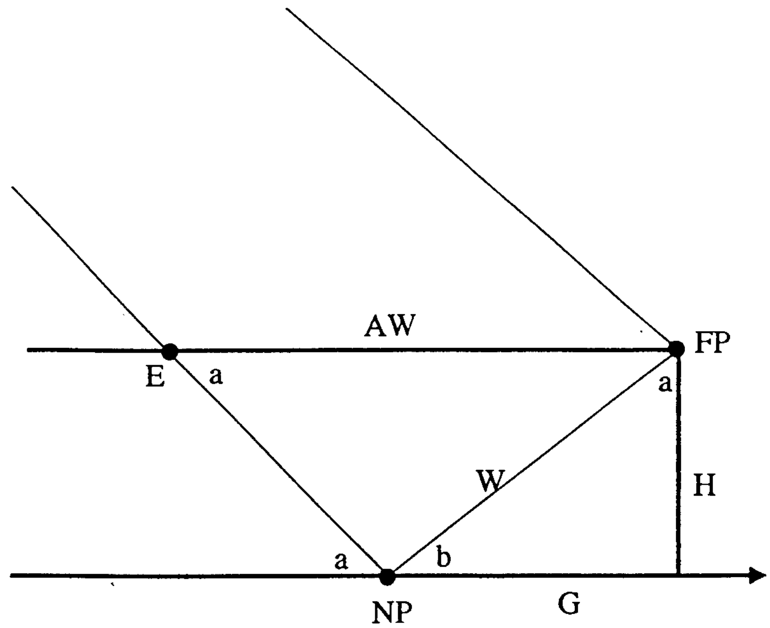

Figure 10 Geometric configuration for calculating the width of a target.

Again, the width W is calculated from using the same theorem.

$$W = \sqrt{G^2 + H^2}$$

V. Conclusion

ISAR imaging is a process that takes three-dimensional objects and maps them into a two dimensional space. This 2-D image space is range and cross range. Using the fine range sampling capabilities of the radar and using Doppler shifts due to the rotational motions of the target forms the image. One problem with ISAR is that the image plane will change as a function of the complex motion of the target. This change will cause the superposition of the target images. The resultant image is therefore blurred in the cross range dimension. Hence image quality is poor compared with conventional SAR

techniques of a non moving target, but orders of magnitude better than SAR for a moving target. Advanced techniques such as Polar Reformatting and Time-Frequecy ISAR have been develop to deal with this problem. Currently depoyed systems, however, do not use these techniques and therefore the lower quality of images that ISAR produces requires intensive training for full image exploitation of the radar operator.

There are several techniques of auto-classifying aids that could be developing in assisting the radar operator. These techniques are described in various IEEE articles that are being develop to assist the radar operator in classify targets. Also new methods are being described within these trade journals that will assist in the imaging of ISAR radars. Such topics include new techniques for beamforming, motion compensation, and imaging. There are also techniques in describing hybrids SAR/ISAR radars All such techniques will increase the usability of the ISAR radar

Even though the images are currently of lower quality, one must remember why ISAR was developed. It was developed to image moving targets. The reason it was develop was that these moving targets were blurring SAR imagery. Now that moving targets are capable of being imaged using ISAR. As new technologies are being developed, it is just a matter of time before the quality of imagery improves.

ISAR radar is used in the US Navy and by the coast guard for various functions. As image processing, resolution, and dynamic range improve, ISAR will have the potential of performing many useful tasks that currently are not possible with present systems.

References

Sun Y., Lin P.; "An improved method of ISAR image processing"; **Proceedings of the 35th Midwest symposium on Circuits and Systems**, 1992; Vol. 2, page 983 – 986.

J. Clarke; **Advances in radar techniques**; ©1985 Peter Peregrinus Ltd., London, UK.

Roger Voles; "Resolving revolutions: imaging and mapping by modern radar"; **IEE Proceedings 1993.**

Frenchy Levesque, Ray Gordon; "Can you picture that?"; **Viking Watch** June 1985; page 8 – 9.

M.J. Pricket, C.C. Chen, "Principles of Inverse Synthetic Aperture Radar (ISAR) Imaging"; **IEEE EASCON Record,** 1980; page 340-345.

George Stimson; **An Introduction to Airborne Radar;** ©1983 Hughes Aircraft Company, El Segundo, CA.

Walter G. Carrara, Ron S. Goodman, Ronald M. Majewski; **Spotlight Synthetic Aperture Radar: Signal Processing Algorithms**; © 1995